

ULTRAHIGH ENERGY TAU NEUTRINOS

J. JONES, I. MOCIOIU, I. SARCEVIC

*Department of Physics
University of Arizona
Tucson AZ 85721*

M. H. RENO

*Department of Physics and Astronomy
University of Iowa
Iowa City IA 52242*

We study ultrahigh energy astrophysical neutrinos and the contribution of tau neutrinos from neutrino oscillations, relative to the contribution of the other flavors. We show the effect of tau neutrino regeneration and tau energy loss as they propagate through the Earth. We consider a variety of neutrino fluxes, such as cosmogenic neutrinos and neutrinos that originate in Active Galactic Nuclei. We discuss signals of tau neutrinos in detectors such as IceCube, RICE and ANITA.

1. Introduction

Ultrahigh energy astrophysical neutrinos provide unique probes of particle physics at energies currently not accessible to collider experiments. In addition, neutrinos point back to their sources and they travel very large distances without interactions, providing valuable information about extreme environments.

The experimental data on $\nu_\mu \leftrightarrow \nu_\tau$ neutrino oscillations¹ implies that astrophysical sources of muon neutrinos become sources of ν_μ and ν_τ in equal proportions after oscillations over astronomical distances². Even though ν_μ and ν_τ have identical interaction cross sections at high energies, signals from $\nu_\tau \rightarrow \tau$ conversions have the potential to contribute differently from ν_μ signals. The τ lepton can decay far from the detector, regenerating ν_τ ³. In case of ν_μ , muons produced via charged-current decay but electromagnetic energy loss coupled with the long muon lifetime make the ν_μ regeneration from muon decays irrelevant for high energies. Another signal of $\nu_\tau \rightarrow \tau$ is the tau decay itself⁴.

We have studied in detail the propagation of all flavors of neutrinos with very high energy ($E \geq 10^6$ GeV) as they traverse the Earth. Because of the high energies attenuation shadows most of the upward-going solid angle at high energies, so we have limited our consideration to nadir angles larger than 80° . We have focused on the contribution from tau neutrinos, produced in oscillations of extragalactic muon neutrinos as they travel large astrophysical distances.

Neutrinos from astrophysical sources are usually produced via pion decays, which determine the flavor ratio $\nu_e : \nu_\mu : \nu_\tau$ to be $1 : 2 : 0$. After propagation over very long distances, neutrino oscillations change this ratio to $1 : 1 : 1$ because of the maximal $\nu_\mu \leftrightarrow \nu_\tau$ mixing. For the GZK flux, ν_e and ν_μ incident fluxes are different because of the additional contributions from $\bar{\nu}_e$ from neutron decay and ν_e from μ^+ decays⁵. Because of this, the flavor ratio at Earth is affected by the full three flavor mixing and is different from $1 : 1 : 1$. Given fluxes at the source $F_{\nu_e}^0$, $F_{\nu_\mu}^0$ and $F_{\nu_\tau}^0$, the fluxes at Earth become:

$$F_{\nu_e} = F_{\nu_e}^0 - \frac{1}{4} \sin^2 2\theta_{12} (2F_{\nu_e}^0 - F_{\nu_\mu}^0 - F_{\nu_\tau}^0) \quad (1)$$

$$F_{\nu_\mu} = F_{\nu_\tau} = \frac{1}{2} (F_{\nu_\mu}^0 + F_{\nu_\tau}^0) + \frac{1}{8} \sin^2 2\theta_{12} (2F_{\nu_e}^0 - F_{\nu_\mu}^0 - F_{\nu_\tau}^0) \quad (2)$$

where θ_{12} is the mixing angle relevant for solar neutrino oscillations. We have assumed that θ_{23} , the mixing angle relevant for atmospheric neutrino oscillations, is maximal and θ_{13} is very small, as shown by reactor experiments, as well as atmospheric and solar data.

For GZK neutrinos⁵ produced by cosmic ray interactions with the microwave background, the flavor ratio at Earth deviates from $1 : 1 : 1$ because the initial fluxes are somewhat different, and they start out in a ratio not equal to $1 : 2 : 0$. In this case the $\nu_e \leftrightarrow \nu_\mu, \nu_\tau$ oscillations relevant to solar neutrino oscillations start playing a role, in addition to the maximal $\nu_\mu \leftrightarrow \nu_\tau$ oscillations relevant to atmospheric neutrinos. Z burst neutrinos⁶ from models with ultrahigh energy neutrinos scattering with relic neutrinos to produce Z bosons are also considered below, where neutrino mixing yields flux ratios of $1 : 1 : 1$.

The initial fluxes for GZK and Z burst neutrinos are shown in Fig. 1. In our propagation of neutrinos and charged leptons through the Earth⁷, we have focused on kilometer size neutrino detectors, such as ICECUBE⁸ and the Radio Ice Cerenkov Experiment (RICE)⁹ and on a detector with much larger effective area which uses Antarctic ice as a converter, the Antarctic Impulsive Transient Antenna (ANITA)¹⁰.

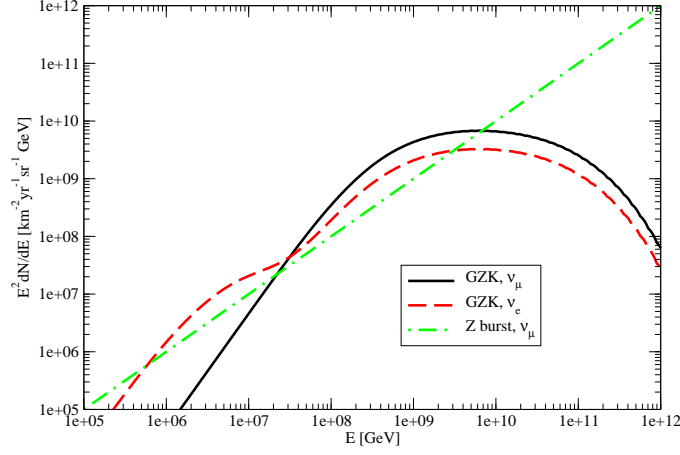


Figure 1. Initial Neutrino Fluxes

Signals of neutrino interactions in the rock below the ice or in ice depend on the energy and flavor of the neutrino. Muon neutrino charged current (CC) conversions to muons are noted by the Cherenkov signal of upward going muons in a detector such as IceCube⁸. High energy electromagnetic showers from $\nu_e \rightarrow e$ CC interactions produce Cherenkov radiation which is coherent for radio wavelengths. The Radio Ice Cherenkov Experiment (RICE) has put limits on incident isotropic electron neutrino fluxes which produce downward-going electromagnetic showers⁹. The Antarctic Impulsive Transient Antenna (ANITA) also uses the ice as a neutrino converter¹⁰. These balloon missions will monitor the ice sheet for refracted radio frequency signals with an effective telescope area of 1M km². All flavors of neutrinos produce hadronic showers. In addition, tau decays contribute to both electromagnetic and hadronic showers that could be detected by IceCube, RICE or ANITA.

2. Neutrino Propagation

Propagation of neutrinos and charged leptons is governed by the following transport equations:

$$\begin{aligned} \frac{\partial F_{\nu_\tau}(E, X)}{\partial X} = & -N_A \sigma^{tot}(E) F_{\nu_\tau}(E, X) + N_A \int_E^\infty dE_y F_{\nu_\tau}(E_y, X) \frac{d\sigma^{NC}}{dE}(E_y, E) \\ & + \int_E^\infty dE_y \frac{F_\tau(E, X)}{\lambda_\tau^{dec}} \frac{dn}{dE}(E_y, E) \end{aligned}$$

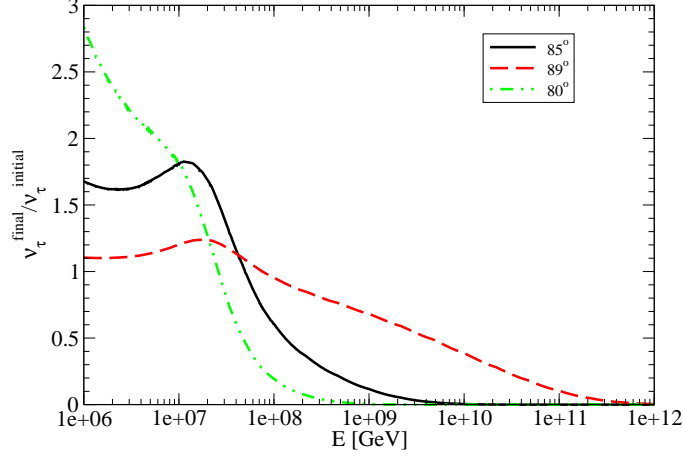


Figure 2. Ratio ν_τ/ν_μ for GZK neutrinos, at nadir angles of 85° and 89° .

$$\frac{\partial F_\tau(E, X)}{\partial X} = -\frac{F_\tau(E, X)}{\lambda_\tau^{dec}(E, X, \theta)} + N_A \int_E^\infty dE_y F_{\nu_\tau}(E_y, X) \frac{d\sigma^{CC}}{dE}(E_y, E) \quad (3)$$

$$-\frac{dE_\tau}{dX} = \alpha + \beta E_\tau \quad (4)$$

Here $F_{\nu_\tau}(E, X) = dN_{\nu_\tau}/dE$ and $F_\tau(E, X) = dN_\tau/dE$ are the differential energy spectra of tau neutrinos and taus respectively, for lepton energy E , at a column depth X in the medium defined by

$$X = \int_0^L \rho(L') dL'. \quad (5)$$

For tau neutrinos, we take into account the attenuation by charged current interactions, the shift in energy due to neutral current interactions and the regeneration from tau decay. For tau leptons we consider their production in charged current ν_τ interactions, their decay, as well as electromagnetic energy loss.

The effective decay length of produced taus does not go above 10^7 cm, even for $E_\tau = 10^{12}$ GeV. This is because electromagnetic energy loss over that distance reduces the tau energy to about 10^8 GeV, at which point the tau is more likely to decay than interact electromagnetically¹¹.

We have found that the ν_τ flux above 10^8 GeV resembles the ν_μ flux. The lore that the Earth is transparent to tau neutrinos is not applicable in

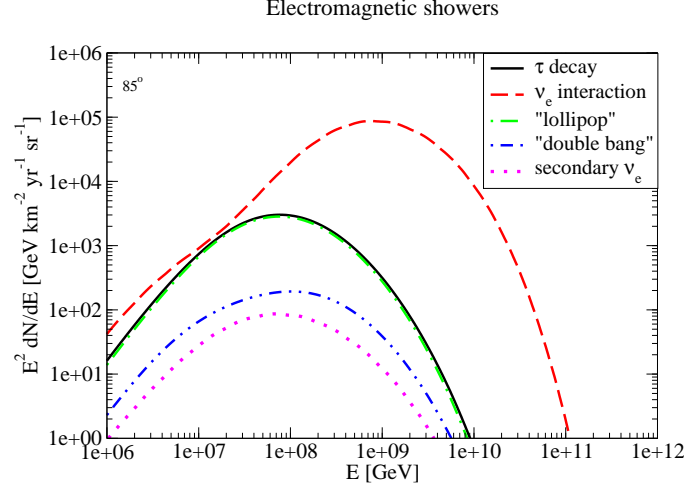


Figure 3. Electromagnetic showers for GZK neutrinos.

the high energy regime. Tau neutrino pileups at small angles with respect to the horizon are significantly damped due to tau electromagnetic energy loss above $E_\tau \sim 10^8$ GeV if the column depth is at least as large as the neutrino interaction length.

At lower energies, $E \leq 10^8$ GeV, regeneration of ν_τ becomes important for trajectories where the other flavors of neutrinos are strongly attenuated, but the ν_τ regeneration is very effective. The regeneration effect depends strongly on the shape of the initial flux and it is larger for flatter fluxes. The enhancement due to regeneration also depends on the amount of material traversed by neutrinos and leptons, i.e. on nadir angle. For GZK neutrinos, we have found that the enhancement peaks between 10^6 and a few $\times 10^7$ GeV depending on trajectory.

Fig. 2 shows the ratio of the tau neutrino flux after propagation to incident tau neutrino flux, for 89° , 85° and 80° . This ratio illustrates a combination of the regeneration of ν_τ due to tau decay and the attenuation of all neutrino fluxes. For 89° , where both the total distance and the density are smaller, the attenuation is less dramatic, and the flux can be significant even at high energy. The regeneration in this case can add about 25% corrections at energies between 10^7 and 10^8 GeV. For 85° the relative enhancement is around 80% and peaked at slightly lower energies, while at 80° it is almost a factor of 3 at low energy. At 80° , however, the flux is very strongly attenuated for energies above a few $\times 10^7$ GeV. It is already clear

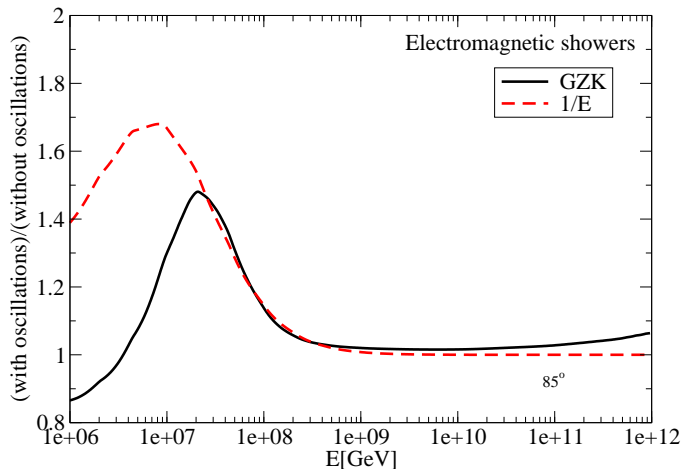


Figure 4. Ratio of electromagnetic shower rates in the presence and absence of $\nu_\mu \rightarrow \nu_\tau$ oscillations for GZK and $1/E$ neutrino spectra for nadir angle 85° for a km size detector.

from here that the total rates will be dominated by the nearly horizontal trajectories that go through a small amount of matter. However, rates can get significant enhancements at low energies where the regeneration from tau decays adds an important contribution even for longer trajectories.

3. Showers

We have translated the neutrino fluxes and tau lepton fluxes into rates for electromagnetic and hadronic showers at selected angles to see the effect of attenuation, regeneration, and the different energy dependences of the incident fluxes. We have focused on comparing the ν_τ contribution to the ν_e and ν_μ contributions to determine in what range, if any, ν_τ 's enhance shower rates. Electromagnetic shower distributions for a nadir angle of 85° are shown in Fig. 3, while Fig. 5 shows hadronic showers.

Fig. 4 shows the ratio of the electromagnetic shower rates at nadir angle 85° in the presence and absence of oscillations for the GZK and Z burst neutrino fluxes (which have a characteristic $1/E$ energy dependence). In absence of oscillations, the only contribution to electromagnetic showers comes from ν_e interactions. In the presence of $\nu_\mu \rightarrow \nu_\tau$ oscillations, electromagnetic decays of taus from tau neutrinos add significant contributions to these rates at energies below 10^8 GeV. In the same time, for the GZK flux, $\nu_e \rightarrow \nu_{\mu,\tau}$ oscillations reduce the number of ν_e 's at low energy, such

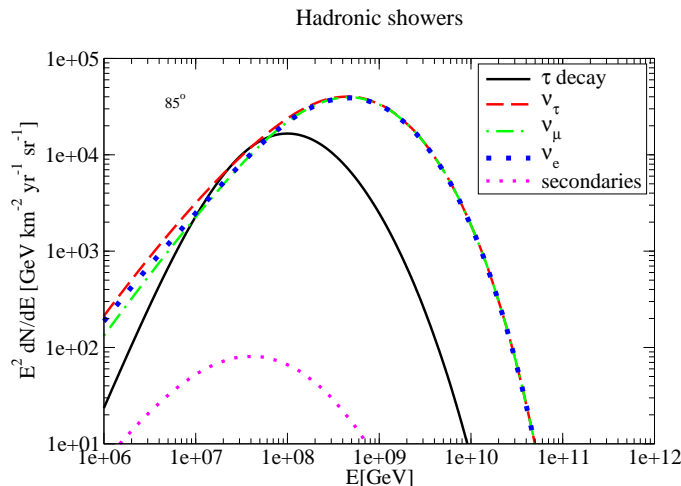


Figure 5. Hadronic showers for GZK neutrinos.

that below a few $\times 10^6$ GeV there are fewer electromagnetic showers than in the absence of oscillations.

The ν_τ flux enhancements depend on the shape of the initial flux. The electromagnetic showers are more sensitive to this shape than hadronic ones. The relative enhancement in hadronic showers is also smaller than for the electromagnetic showers. This is because for the electromagnetic signal the only contribution in the absence of taus is from electron neutrinos, while for hadrons the tau contribution is compared to a much larger signal, from the interactions of all flavors of neutrinos. We have considered contribution from secondary neutrinos, which we find to be relatively small for all fluxes.

For kilometer-sized detectors, at for example a nadir angle of 85° , the maximal enhancement due to ν_τ contribution to electromagnetic shower rates for the GZK flux is about 50% at 3×10^7 GeV, while for a $1/E$ flux, it is even larger, about 70%, at slightly lower energy. These energy ranges are relevant for IceCube. For energies relevant to RICE, tau neutrinos do not offer any appreciable gain in electromagnetic shower signals compared to $\nu_e \rightarrow e$ CC interactions, and they contribute at essentially the same level as ν_μ to hadronic shower rates through NC interactions.

In Fig. 6 we show the ratio of electromagnetic and hadronic shower rates in the presence and absence of $\nu_\mu \rightarrow \nu_\tau$ oscillations. The maximum enhancement due to the presence of ν_τ is about 40% at this angle, as expected since this trajectory has low column density. However, as previously

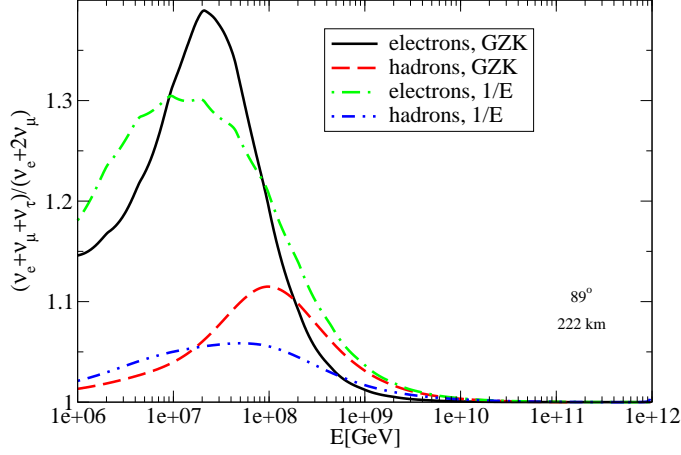


Figure 6. Ratio of electromagnetic and hadronic shower rates in the presence and absence of $\nu_\mu \rightarrow \nu_\tau$ oscillations for GZK and $1/E$ fluxes of neutrinos for detection over 222 km of ice.

discussed, the enhancement occurs in a larger energy range and it peaks at higher energy than in the case of a small size detectors. In 1 km only taus with energies below a few $\times 10^7$ GeV have a significant probability to decay, while much higher energy taus can decay over the total distance of more than 200 km.

At very high energies tau neutrinos do not contribute large signals to kilometer-sized detectors because high energy tau decay lengths are very large, so the probability of a tau decaying in the detector is low. For detectors like ANITA which can sample long trajectories through the ice, one would expect a larger tau neutrino contribution to the signal from tau decay. Despite the long trajectory (222 km with a maximum depth of 1 km for a neutrino incident at 89° nadir angle) the tau contributions to the electromagnetic shower rate is quite small for fluxes expected to contribute in the ANITA signal. For hadronic showers, the suppression of τ decay to hadrons relative to ν_e NC interaction contributions is about the same as for electromagnetic showers compared to $\nu_e \rightarrow e$. The ν_τ contribution to the hadronic shower rate from interactions is about the same as the ν_e contribution. Clearly, large detectors with energy threshold below 10^8 GeV and with very good angular resolution are needed for distinguishing between different neutrino flavors.

Recently, it has been noted that rock salt formations have similar properties to the Antarctic ice and can therefore be used as large scale neu-

trino detectors¹⁴. Salt has a higher density ($\rho_{salt} = 2.2 \text{ g/cm}^3$) than ice ($\rho_{ice} = 0.9 \text{ g/cm}^3$), so it is possible to achieve an effective detection volume of several hundred km^3 water equivalent in salt. This is somewhat better than RICE but with a much smaller actual detector size. The threshold for detecting the radio signal from showers in salt is of the order of $\sim 10^7$ GeV. Another recently proposed experiment is LOFAR¹⁵, a digital telescope array designed to detect radio Cherenkov emission in air showers. LOFAR has sensitivity in an energy range of $\sim 10^5 - 10^{11}$ GeV, so it can detect showers at much lower energies than other radio Cherenkov experiments. LOFAR will likely be configured to detect horizontal showers from skimming neutrinos as well. With its low energy threshold, LOFAR has an excellent opportunity to observe the shower enhancement at lower energies due to ν_τ regeneration and tau pileup, which is not easily accessible in ANITA.

Acknowledgments

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